Hydrogen Infrastructure Delivery Reliability R&D Needs

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Prepared by:

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Abstract

For a viable hydrogen economy to develop, the means must be found to solve the "chicken and egg" problem of making hydrogen widely available so that hydrogen end-users will begin to purchase hydrogen-based systems. This is a daunting challenge, which must be overcome if a hydrogen economy is to develop. Competent analysts opine that early hydrogen distribution on a large geographical scale will probably depend on the widespread use of small-scale, local hydrogen generators, such as small natural gas reformers and electrolyzers. As the transition progresses, larger scale hydrogen production plants will likely be built. Those plants will need ways to market their hydrogen, because such plants are likely to be built before a dedicated, national hydrogen transmission and distribution system is fully functional. Few dedicated hydrogen pipelines exist to distribute large volumes of hydrogen over long distances, so larger diameter and higher-pressure pipelines will be required. There are several means for moving central station hydrogen into the economy: constructing large scale dedicated hydrogen pipelines, moving pure hydrogen through existing natural gas pipelines, and adding hydrogen to the existing natural gas system allowing it to be consumed along with natural gas in existing natural gas appliances. These options in many ways could fill a major gap in a national transition-to-hydrogen. Because these approaches are potentially attractive and, because so many issues would need to be resolved before such options could be adequately evaluated, it is recommended that a related analysis, research, development and demonstration program be initiated in the near future.

Purpose

The purpose of this white paper is to identify challenges and options related to the period of transition from the current U.S. energy infrastructure to one in which hydrogen plays a major role as an energy carrier. The primary focus is on the use of existing natural gas pipelines for mixed natural gas-hydrogen use.

Introduction

Hydrogen has the potential to become a major energy carrier in the future U.S. energy system. In his National Energy Policy, President Bush acknowledged hydrogen as an alternative energy carrier with promise and recommended that the Department of Energy (DOE) "focus research and development (R&D) efforts on integrating current programs regarding hydrogen, fuel cells, and distributed energy." In response, DOE developed a national vision for hydrogen and a related program for research and development (Hydrogen, Fuel Cells & Infrastructure Technologies Program. DOE. June 3, 2003 – Draft).

Hydrogen does not exist in nature in a form that is useable for energy purposes. Rather, it exists as a component of water, hydrocarbon fuels, and other substances. Accordingly, energy from a primary source must be expended to liberate hydrogen. Once produced, hydrogen for energy applications must be transported to the point of end-use by one or more methods. The focus of this white paper is on hydrogen delivery from a central processing facility by gas pipeline, and particular emphasis is placed on the possible use of the natural gas transportation, storage, and distribution system in a transition to a hydrogen economy.

While the transport, storage, and distribution of natural gas is a well-developed commercial enterprise, the challenges of consumer use of hydrogen are more complex because of the unique nature of hydrogen. For instance, hydrogen can diffuse through and embrittle pipes unless they are constructed of specially selected materials. Hydrogen also has a wide explosive range and extremely low ignition energy, which creates a number of safety challenges. Also, codes, standards, and regulations covering hydrogen transport, storage, and use differ from those for natural gas.

Although hydrogen is safely and effectively being produced, transported, stored, and used in the petrochemical and refining industries and for specialty applications, it is not as commercially widespread as natural gas. There is no large-scale national hydrogen infrastructure, and building one will require enormous investment. Furthermore, a transition from the current energy system to one heavily dependent on hydrogen will require a complex phasing that will likely utilize relatively expensive interim steps before the commitment to a national hydrogen infrastructure.

1.0 Background

In the long term, a new grass-roots effort dedicated to a national hydrogen pipeline, storage, and distribution system will likely be required to establish a viable hydrogen economy. Such an undertaking will require a major national commitment and enormous levels of investment, neither of which will be forthcoming without a reasonably established and assured market for the hydrogen. One of the greatest challenges will be how to most effectively provide hydrogen to end-users in sufficient quantities prior to a large-scale hydrogen economy in order to build a demand-base that justifies the construction of a full-blown national hydrogen production and distribution system.

At present, the United States has extensive systems for producing, transporting, and delivering electricity, natural gas, petroleum, and petroleum products. The natural gas system is most often referred to as the model for an ultimate hydrogen system. Indeed, the use of the natural gas system might well facilitate a transition to a hydrogen economy, but, before we consider that use, let us first review some basic hydrogen facts.

1.1 Hydrogen Basics

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas. It is the lightest element, having the smallest molecular size and weight. In its native state, hydrogen exists as a diatomic molecule. Hydrogen is the most abundant element in the universe, estimated to account for 90% by weight. However, it is not commonly found in its elemental form on earth since it readily combines with other elements.

Hydrogen has a wide flammability range in air, coupled with its very low ignition energy. A hydrogen/air mixture can burn in concentrations between 4 and 75%, as compared to natural gas at 5 and 15%, and hydrogen can ignite with as little as 0.02 mJ of energy (Hydrogen Vehicle Safety Report. DOE. 1997).

Hydrogen has high energy content by weight (nearly three times as much as gasoline) but its energy density per volume is very low at standard temperature and pressure. To compensate for hydrogen's low volumetric energy density, hydrogen must be pumped at 2.8 times the rate of natural gas to deliver the same energy through a pipeline (Hydrogen – Status and Possibilities. Bellona Report. 2002).

As a result of the unique properties that have been highlighted, large-scale transmission and distribution of hydrogen through natural gas pipelines face challenges that must be evaluated and remedies identified before the approach can be seriously considered for implementation.

Hydrogen can be transported as a gas at low (100-300 psig) or high (3000-5000 psig) pressure or as a cryogenic liquid. It can be transported by gas pipelines, gas or cryogenic liquid trucks, tube trailers, barge, or rail cars (Hydrogen, Fuel Cells & Infrastructure Technologies Program. DOE. June 3, 2003 – Draft). Currently however, as shown in Figure 1, pipeline transportation of hydrogen is more widespread than any other means of transportation

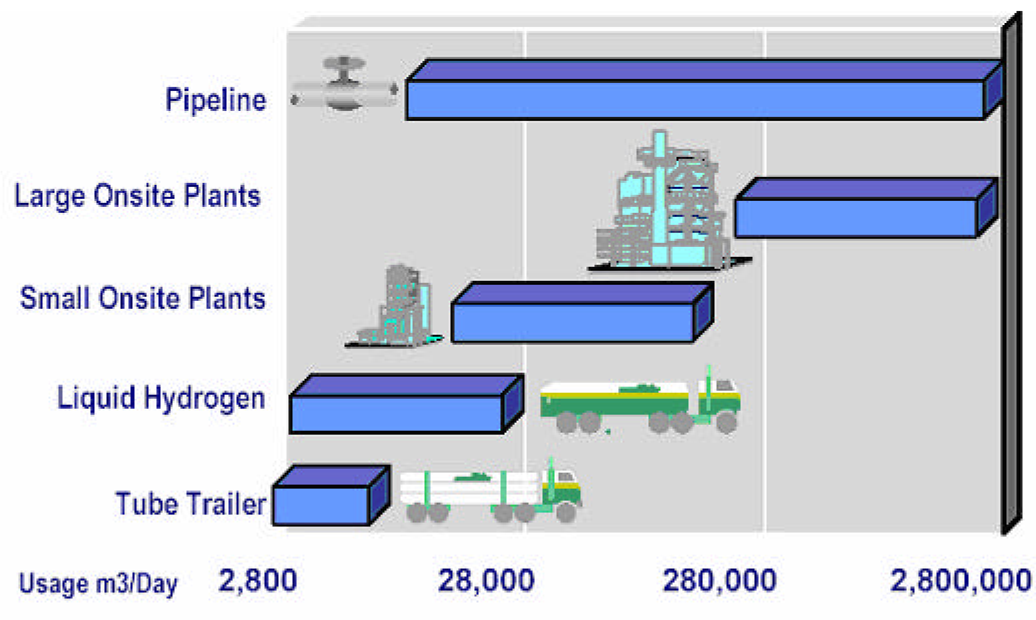

Figure 1 Hydrogen Distribution and Transportation Methods (Source: Air Products)

1.2 The Existing Hydrogen System

At present, hydrogen is produced in a number of plants and is used primarily in the manufacture of chemicals and petroleum products. Hydrogen is typically moved as a gas through pipelines, but it can also be shipped in a compressed state in high pressure cylinders, or it can be chilled to very low temperatures and shipped as a cryogenic liquid. Much experience world-wide has been gained over many years to make these transportation modes safe and efficient. However, if the volume of hydrogen use grows, new safety and cost issues will surface, requiring major infrastructure changes (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004).

Hydrogen pipelines are currently limited to a few areas of the United States where large hydrogen refineries and chemical plants are concentrated. Figure 2 shows the most extensive U.S. hydrogen pipeline system, which lies in the Gulf Coast region, the home of a number of large refineries and chemical plants.

The United States has approximately 1,126 km [700 miles] of hydrogen pipeline network and Europe has about 1,529 km [950 miles] (Hearing on the Energy Pipeline Research, Development, and Demonstration Act. Air Products. 2002). Hydrogen pipes in use today typically operate at pressures between 150-300 psi with a diameter of 25.4 – 30.48 cm [10-12 inches].

The oldest existing hydrogen pipeline system is found in the Ruhr Valley area of Germany and is 225.3 km [140 miles] long (Hydrogen – Status and Possibilities. Bellona Report. 2002). This network has been in use for 50 years without any major accidents. The longest hydrogen pipeline runs 402.3 km [250 miles] between France and Belgium. Table 1 lists existing hydrogen pipelines in service today in the United States and Europe.

Figure 2 Air Liquide Gulf Coast and Mississippi Pipeline Networks (Source: Air Liquide)

2.0 Transition to a Hydrogen Economy

If it develops, a hydrogen economy will evolve over a number of decades because of the time it takes for the introduction of new technologies and the long turnover of capital stock. While hydrogen can, in principle, be used in many energy applications, its most discussed use is as a substitute for petroleum-based fuels in light-duty transportation vehicles.

A well-developed hydrogen economy will make use of the lowest cost sources of hydrogen, delivered as appropriate to end-users. The economics of current and foreseeable hydrogen production systems indicate that central station natural gas and coal are the two lowest cost hydrogen sources, followed by various electrolysis-based systems (Hydrogen, Fuel Cells & Infrastructure Technologies Program. DOE. June 3, 2003 – Draft). Central station hydrogen generation will require an enormous investment in a new hydrogen pipeline system. Related investments would be extremely difficult to justify at the beginning of a transition to hydrogen because of huge uncertainties and risks.

Table 1 Hydrogen Pipelines Currently In Use (Source: Ogden, J)

Company	Location	Operation years	Pressure (psi)	Length (miles)	Flow rate (million SCF/day)	Pipe diameter (in)	H_2 purity (%)
Air Products and Chemicals	La Porte, TX	Since 1970s	50-80	125	40	4-12	99.5
	Plaquemine, LA	-	-	175	30	-	-
Praxair	Texas City – Bayport – Port Arthur, TX	Since 1970s	-	-	100	8	-
	Carney's Point, NJ	-	-	-	6	-	-
	Whiting, IN	-	-	-	5	-	-
Air Liquide	Since mid-1980s	France; Belgium	1470	250	17	4	99.995
ICI	Teeside, England	Since 1970s	750	10	20	-	95
Chemische Werk Huls, Ag	Ruhr Valley, Germany	Since 1938	360	140	100	4-12	95

Accordingly, at the outset of a transition to a hydrogen economy, distributed hydrogen generation will almost certainly be required in order to provide hydrogen on a large scale, at a minimum, for the development of hydrogen-fueled light duty vehicles (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004.) Analysis shows that this approach is the only practical method of beginning a hydrogen economy, since consumers will not buy hydrogen-fueled vehicles that cannot be conveniently fueled. This has been popularly described as the hydrogen "chicken and egg problem."

As a hydrogen economy expands, it is almost universally agreed that it will be necessary to begin to build central-station hydrogen generation plants. At that point, the challenge will be to provide a means for the resulting hydrogen to be distributed, because rational development will surely require the construction of multiple central station hydrogen plants prior to or in parallel with the construction of a large-scale, dedicated hydrogen transmission pipeline system. An intriguing option for early-phase hydrogen off-take would be to mix and distribute it in existing natural gas pipelines. Such an arrangement is feasible, because it has already been demonstrated that 20-30% hydrogen added to natural gas will burn without problems in most existing natural gas appliances in homes and commercial buildings. The addition of hydrogen to natural gas would also have the benefit of reducing the national demand for natural gas imports.

3.0 Natural Gas Pipeline Use Now and in the Future

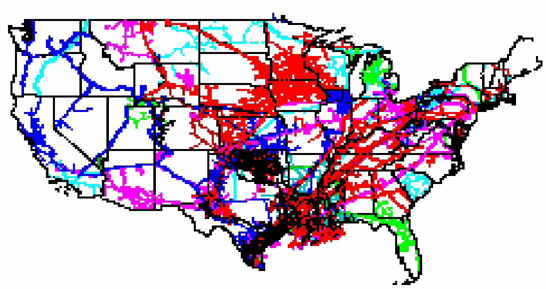

Figure 3 Existing Natural Gas Pipeline Network in the United States (Source: DOE/NETL)

The efficient and effective delivery of natural gas from production to end-users utilizes an extensive and elaborate transportation system. There are two major types of pipelines: large-diameter, high-volume interstate transmission lines and smaller diameter, lower volume distribution lines. Transmission pipelines are typically 60.96 and 91.44 cm [24 and 36 inches] in diameter and are made of carbon steel (naturalgas.org, 2003). Distribution pipelines, on the other hand, usually operate around 3 psi because the pressure required for moving natural gas through the distribution network is much lower. Distribution pipes are typically 15.24 – 40.64 cm [6-16 inches] in diameter, but can be as small as 1.27 cm [0.5 inches] in diameter (naturalgas.org, 2003).

In transmission pipelines, natural gas pressure decreases with distance away from compressors due to friction losses. Accordingly, recompression is required periodically along the pipe. This is achieved by compressor stations, typically placed every 64.37 to 160.93 km [40 to 100 miles] (naturalgas.org, 2003). Natural gas pipelines include a multitude of valves along their entire length to adjust for varying conditions and demands and to terminate flow in case of emergencies. These valves are typically placed every 8.05 to 32.19 km [5 to 20 miles] along pipelines (naturalgas.org, 2003).

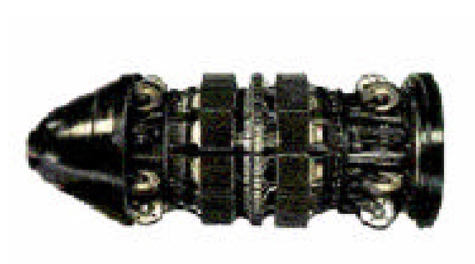

Figure 4 Smart Pig Technology used in Natural Gas Pipelines (Source: Air Liquide)

Inspection devices, known as "smart pigs," are inserted into pipelines and propelled by gas flow to inspect pipes to locate pipeline abnormalities before they become significant. Pigs can measure pipe thickness and roundness, check for signs of corrosion, and detect minute leaks and other defects along the interior of the pipe. Other maintenance and safety measures associated with natural gas pipelines include aircraft inspection patrols, fixed and mobile leak detectors, pipeline markers, gas sampling, and emergency response teams to name a few.

While U.S. use of natural gas may wane later this century, no credible analyst has projected that its use will be terminated, even if hydrogen and/or electricity replace many natural gas applications. Accordingly, there is currently no basis for believing that the U.S. natural gas pipeline system will be abandoned in the foreseeable future. Indeed, the introduction of methane from coal, biomass or hydrates could prolong the use of our natural gas transmission and distribution system beyond the scope of any credible forecaster. Therefore, we do not believe that it is reasonable to expect that the existing natural gas pipeline system will be available for exclusive hydrogen transportation within any practical planning horizon.

4.0 Issues Related to Natural Gas and Hydrogen Systems

While natural gas and hydrogen are both gases, their physical and chemical properties are very different. Table 2 displays many of these differences, some of which will be important in the subsequent discussion.

Table 2 Selected properties of Hydrogen and other Fuel Gases

Property	Gasoline	Methane	Hydrogen
Density (kg/m^3)	4.40	0.65	0.084
Diffusion Coefficient In Air (cm^2/sec)	0.05	0.16	0.610
Specific Heat at Constant Pressure (J/Gk)	1.20	2.22	14.89
Ignition Limits In Air (vol %)	1.0-7.6	5.3-15.0	4.0-75.0
Ignition Energy In Air (mJ)	0.24	0.29	0.02
Ignition Temperature (^{o}C)	228-471	540	585
Flame Temperature In Air (^{o}C) Explosion	2197	1875	2045
Flame Emissivity (%)	34-43	25 -33	17-25
Density Relative to Air	4.0	0.55	0.07
Molecular Weight	107	16	2
Explosive Energy (MJ/ m^3)	407	32	9
Flame Speed (cm/s)	42	43	346
Detonation Range (% by volume)	1 -3	6-14	18-59

Source: T. Nejat Veziroglu. Hydrogen Energy System: A Permanent Solution to Global Problems, and Nyborg et al. (2003).

Since hydrogen is the smallest element, it has a greater tendency to escape through small openings than natural gas. Based on diffusion in air, for example, one would expect hydrogen to escape at a rate 3.8 times faster than natural gas based on their diffusion coefficients shown in Table 2 (Hydrogen Vehicle Safety Report. DOE. 1997). If pipeline systems are not appropriately designed and constructed, hydrogen is more likely than natural gas to seep through valves, seals, gaskets, and even pipes, possibly creating safety hazards. In addition, hydrogen leaks are difficult to detect and odorants, commonly used to allow human detection of natural gas leaks, are not used with hydrogen because of hydrogen purity demands.

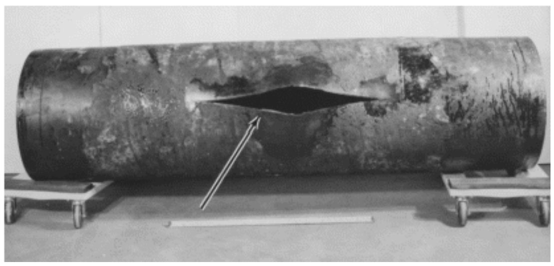

Figure 5 Pipeline Fracture Caused by Hydrogen Embrittlement (Source: National Tranportation and Safety Board)

Many steels are prone to hydrogen embrittlement, which means prolonged exposure to hydrogen can cause these steels to lose strength, leading eventually to failure. This is especially true for modern high strength steels which are commonly used in new natural gas pipeline construction. As a result, adding hydrogen to natural gas transmission lines will necessitate evaluating the potential interactions that various pipeline materials have with hydrogen to assess the potential for hydrogen embrittlement, leaks, and the compatibility of all pipeline components including compressors and valves.

Regulatory issues are of great importance whenever dealing with potentially dangerous gases. For instance, the Department of Transportation's regulation (29 CFR 1910.103) states that hydrogen pipelines are to be located above ground. In practice, there are exceptions to this rule. The basis and background of this and related rules must be understood and means developed for change if existing natural gas pipelines are to be used for partial hydrogen service. In the long-term future, new hydrogen-only pipelines would most likely require underground transmission and distribution.

Figure 6 Example of an Above Ground Pipeline (Source: DOE/NETL)

Public awareness and acceptance are also a potential challenge to the widespread use of hydrogen. The general public will have to be educated on the technological advantages of hydrogen as well as the realities of hydrogen safety. Strong public acceptance is essential if hydrogen is to be distributed and used in urban, rural, and suburban areas. (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004.)

5.0 Hydrogen Pipeline Possibilities

A well-developed hydrogen economy will make use of the lowest cost sources of hydrogen, delivered as appropriate to end-users. Central station hydrogen generation will require an enormous investment in a new hydrogen pipeline system. Related investments would be extremely difficult to justify at the beginning of a shift to hydrogen because of huge uncertainties and risks. A large challenge will be justification for the construction of multiple central station hydrogen plants prior to the construction of major dedicated hydrogen transmission pipelines. One potentially attractive option would be the addition of hydrogen to natural gas in the existing natural gas pipeline system.

6.0 Use of Existing Natural Gas Pipelines for Hydrogen Service

6.1 Natural Gas / Hydrogen Mixture Addition Approach

The use of the natural gas transmission system may be a viable solution to bridging an important gap in the evolution of a national hydrogen economy, namely to provide off-take from large, central, hydrogen production plants before major hydrogen pipelines come into nationwide operation.

To establish the viability of mixing hydrogen and natural gas, it will be necessary to identify how natural gas/hydrogen mixtures will behave in existing natural gas transmission and distribution pipelines and natural gas end-use appliances. This will require a significant level of research and development involving the careful consideration of a number of technological issues as well as related codes and standards. Where problems are identified, options for change will need to be developed and evaluated. Considerable effort will be required to demonstrate safety at all points along a natural gas/hydrogen system, and it is certain that codes and standards will have to be appropriately modified. Once the behavior of hydrogen in natural gas pipelines has been analyzed and problems have been identified and resolved, the nation will be able to intelligently determine if the mixture option is desirable and cost-effective.

There is precedent for the mixture option. In the early days of gaseous fuel distribution, dating back to the 1800s, so-called "town gas", a mixture of methane, hydrogen, and nonfuel gases, was widely distributed. Town gas was first produced from coal and consisted of roughly 50% hydrogen, 30% methane, and various amounts of carbon monoxide (CO) and carbon dioxide (CO_2). Early town gas pipelines were typically operated at low pressure and composed of an assortment of materials including wood, cast iron, and low strength steels. Unlike today's high strength carbon steels, the low strength steels of the day were not particularly susceptible to hydrogen embrittlement. Over time, town gas was replaced by natural gas, which was more economic.

While the economies are not yet known, it is technically possible to separate hydrogen from natural gas via membrane separation or adsorption. Then, hydrogen could be removed at various locations for use in pure hydrogen applications. Potential combustion benefits such as lower

NO_x and CO_2 emissions have been offered as a rationale for justifying the added cost of using a natural gas/hydrogen mixture in large combustors.

6.2 The Direct Hydrogen Addition Approach

Use of existing natural gas pipeline network for exclusive transmission of pure hydrogen, though not realistic in the foreseeable future, is a possibility for the transition to a hydrogen economy but because of diffusion losses, brittleness of materials and seals, safety (real and imagined), hydrogen's low volumetric energy density, and other non-technical and regulatory issues, the challenges of large scale transmission of hydrogen are real and must be addressed prior to start-up. These issues/challenges are described in some detail below.

6.3 Issues and Challenges Associated with Hydrogen Addition Approaches

6.3.1 Safety

Safety is an issue with hydrogen production, transmission and distribution, storage, and end-use. Safety will also be a major concern related to the mixture approach. Table 3 shows that hydrogen is, in some ways, safer than gasoline or methane as a fuel.

Table 3 Safety Ranking of Fuels (Source: Ocean Engineering and Energy Systems)

Characteristic	Fuel ranking		
	Gasoline	**Methane**	**Hydrogen**
Toxicity of Fuel	3	2	1
Toxicity of Combustion	3	2	1
Density	3	2	1
Diffusion Coefficient	3	2	1
Specific Heat	3	2	1
Ignition Limit	1	2	3
Ignition Energy	2	1	3
Ignition Temperature	3	2	1
Flame Temperature	3	1	2
Explosion Energy	3	2	1
Flame Emissivity	3	2	1
Totals	30	20	16
Safety Factor	0.53	0.8	1
1 – safest; 2 – less safe; 3 – least safe			

If hydrogen were to be added in increasing quantities to the natural gas system, it would impact a variety of processes. Existing natural gas leak detection systems would surely require modification. Leaks could be caused by corrosion, hydrogen embrittlement, and hydrogen diffusion and would need to be detected and repaired on a timely basis. Therefore, mixture-specific leak and corrosion detection devices would need to be developed for mixture service if natural gas pipelines are to be safely converted to carry hydrogen.

Most natural gas distribution pipelines are located underground where they are vulnerable to third-party damage. If existing natural gas pipelines are to be converted for natural gas/hydrogen service, then the issue of third-party damage could become more pronounced. Again, careful analysis is required.

6.3.2 Pig Inspections

Inspection devices for pipelines, called "Pigs," are used for internal pipeline inspections for pipelines 10 inches in diameter and larger. In order to use pigs in natural gas/hydrogen mixture pipes, modifications to existing technologies would almost certainly be required.

6.3.3 Sensors

The introduction of hydrogen into natural gas pipelines may cause hydrogen embrittlement at various operating conditions. To prevent rupture due to embrittlement, the development of new ultrasonic sensor technologies, possibly similar to those used in natural gas pipelines, may be required.

6.3.4 Security

Technologies that can more effectively guard against sabotage or attack on the pipeline network would need to be designed and implemented. For public acceptance of a mixture network, security measures must be convincing.

6.3.5 Diffusion Losses

Hydrogen diffusion losses through seals, gaskets, valves, and fittings designed to contain natural gas will be greater than with natural gas. This is due to the small size of the hydrogen molecule and its low viscosity, as compared to natural gas. Hydrogen can also be absorbed by or permeate pipe walls. Development of suitable and economic materials for seals, gaskets, valves, and fittings maybe required.

6.3.6 Hydrogen Embrittlement

Steel piping exposed to hydrogen can become embrittled--a condition characterized by a degradation of mechanical properties, including increases in surface cracking and crack propagation rates, and ultimately pipe failure. The susceptibility to hydrogen embrittlement depends on the composition of the steel, operating temperatures and pressures, and the concentration of hydrogen in a hydrogen gas/natural gas mixture. Alloy types and levels and surface finish can influence susceptibility to embrittlement, while oxide surface coatings can help reduce hydrogen embrittlement.

Field experience indicates that welded joints can be susceptible to hydrogen embrittlement. The degree to which hydrogen embrittlement is a problem in existing natural gas piping depends on the steel used in the piping and the welding techniques utilized. Older pipelines constructed of high-carbon steels are at greater risk than newer pipelines constructed of low-carbon steels. Operation at higher pressures also increases hydrogen embrittlement risks. Methods to determine the suitability of existing pipelines for mixture service are needed, and lining materials may also be considered.

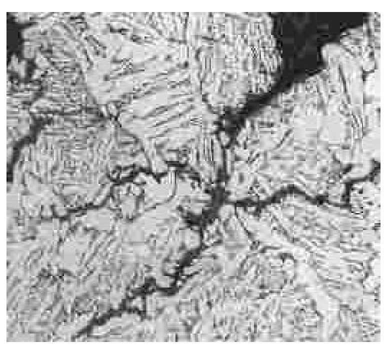

Figure 7 Microscopic View of Pipeline Damage Caused by Hydrogen Embrittlement (Source: Metallurgical Consultants)

6.3.7 Hydrogen Energy Density

Due to the low volumetric energy density of hydrogen as compared to natural gas (about 1/3 the energy content per unit volume), the volumetric flow rate of hydrogen will impact the energy delivered to end-users in mixture service. As a result of the higher hydrogen volumetric flow requirements per unit of energy delivered, higher power compressors may be needed, depending on a variety of factors, including the concentration of hydrogen in the mixture. Typical natural gas compressor energy requirements are about 0.3% of the energy content of the volume of natural gas delivered for every 150 km [90 miles] of pipeline, whereas the energy required for pure hydrogen compression is 1.3% of the energy content of the volume of hydrogen delivered for every 150 km [90 miles] of pipeline (Air Liquide: Hydrogen Delivery Technologies and Systems; Pipeline Transmission of Hydrogen. 2003). Accordingly, transporting natural gas/hydrogen mixtures in the existing natural gas infrastructure may result in a capacity de-rating (on a delivered energy basis). Related analysis will therefore be required to establish limitations or the need for system upgrades, all of which will be very energy system demand-dependent.

6.3.8 Leak Detection

Since hydrogen is odorless, colorless, and burns with a flame that is not visible, its detection is extremely difficult. Natural gas is spiked with odorants, e.g., mercaptans, organic sulfides, which will facilitate leak detection of natural gas/hydrogen mixtures. However, sulfur containing odorants (e.g., mercaptans, organic sulfides) are generally not suitable as hydrogen odorants, if the hydrogen is to be used in fuel cells. This is because the sulfur can damage fuel cell catalysts, reducing fuel cell performance and requiring premature replacement of the fuel cell. Finding a suitable non-sulfur based odorant is problematic because any odorant would have to have a dispersion rate similar to hydrogen's. Leak-detection devices used for natural gas service will have to be tested, modified, or possibly replaced to ensure proper calibration for natural gas/hydrogen mixture service.

6.3.9 Compressors

Existing natural gas compressors are typically of reciprocating or centrifugal design. Existing equipment will need to be certified for hydrogen/natural gas mixture service, and some compressors may have to be replaced, depending on the hydrogen concentrations planned. Again, a detailed understanding will be required, along with the possible need for new certification procedures.

Incompatibility of compressor lubricants with hydrogen is another possible challenge in the conversion of natural gas pipelines to mixture service, because many oils used for natural gas compressors are not suitable for use with hydrogen. Replacement of such oils with oils designed for use in hydrogen specific equipment may be required.

6.3.10 Financing

The cost of conversion of the natural gas transmission and distribution system to natural gas/hydrogen service will be an issue. Natural gas pipeline operators historically have not funded research and development. It may be necessary for government to provide funding and an appropriate regulatory environment to start the process of conversion of natural gas pipelines. The magnitude of the related requirements and the timing of government actions will need to be evaluated.

7.0 Hydrogen Distribution

It is not yet known how hydrogen will be delivered to vehicles (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004). That choice will have a large impact on the nature and cost of the infrastructure necessary to support a significant fleet of fuel cell vehicles, and the issues associated with pipeline delivery of hydrogen. Three general scenarios for distribution of hydrogen can be envisioned:

- **Resource-centered** – In the resource-centered model, hydrogen is produced close to a fossil fuel source, then transported, stored, and distributed locally for use in vehicles or stationary applications. Pipelines that support this production and distribution option would need to be several hundred miles long to deliver hydrogen to supply facilities or to regional distribution centers.

- **Market-centered** – In the market-centered model, hydrogen feedstocks (i.e. fossil fuels or electric power) are distributed to markets that have significant concentrations of fuel-cell vehicles or stationary installations. Hydrogen can then be produced and distributed short distances to individual refueling stations. This option would require shorter pipelines than the resource-centered option to transport hydrogen from production facilities to regional market centers.

- **Distributed** – In the distributed model, either a fossil fuel or electricity is used to produce hydrogen in local refueling stations for the end-user. Since hydrogen is produced very near distributed end-use markets; minimal pipelining would be required to support this option. This is the most likely option for the near term, in the recent National Academies Report entitled "The Hydrogen Economy: Opportunities, Costs, Barrier, and R&D Needs".

8.0 Comparative Analysis of Infrastructure Options

Delivery options must be assessed in the context of a total system. Careful systems analysis will be needed to evaluate the costs and benefits of each option. Such an undertaking will take significant time and effort. A solidly- based evaluation of the natural gas/hydrogen mixture option will not be possible without a significant amount of research, development, and analysis, which is one reason for beginning a related DOE program at an early date.

9.0 New Dedicated Hydrogen Pipelines

As previously noted, dedicated hydrogen pipeline systems exist in the Gulf Coast region of the U.S., and elsewhere in the world. The characteristics of a future large-scale hydrogen pipeline will depend on the hydrogen production infrastructure, the balance between central and distributed production facilities, and how pipelines compare to other hydrogen delivery options. The size of the pipelines, the number and size of compressors and a host of other factors will be affected by the nature of the overall production, storage, and delivery system.

Figure 8 Example of an Existing Pipeline System (Source: DOE/NETL)

Developing a safe and affordable, dedicated, long-distance hydrogen transmission and distribution pipeline network will pose technical and regulatory challenges, many of which need technology-based solutions. Public acceptance and the development of new codes and standards for safe handling of hydrogen will be required (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004). The issue of building a dedicated national hydrogen pipeline system is complex and well beyond the limited scope of this paper, however the following two priority areas for R&D are worth mentioning:

9.1 Odorants

Attempts to odorize hydrogen gas have been unsuccessful, so far, since the hydrogen molecule is so much smaller than any known odorant and hydrogen will escape any known system well ahead of a large molecule odorant. Odorant R&D efforts would include:

- Identification of ideal candidates for hydrogen leak and flame detection from cost, human threshold, flow characteristics, toxicity, flammability, and environmental impact perspectives
- Field demonstration of odorants for hydrogen transportation.

9.2 Codes and Standards

New codes and standards would also need to be developed. For example, CFR 1910.103 mandates above-ground location of gaseous hydrogen pipelines which would be unacceptable in a massive, new hydrogen system.

10.0 Conclusions and Recommendations

If it is to happen, the transition to hydrogen economy will require decades. (National Research Council. The Hydrogen Economy: Opportunities, Costs, Barriers, and R & D Trends. National Academies Press. 2004). The costs and risks associated with moving directly from our existing energy infrastructure to a fully functional national hydrogen system make that approach impractical. For a viable hydrogen economy to develop, means must be found to solve the "chicken and egg" problem of making hydrogen widely available so that hydrogen end-users will begin to purchase hydrogen-based systems. This is a daunting challenge, which must be overcome if a hydrogen economy is to develop.

Early hydrogen distribution on a large geographical scale will probably depend on the widespread use of small-scale, local hydrogen generators, such as small natural gas reformers and electrolyzers. As the transition progresses, larger scale hydrogen production plants will likely be built, because of their indicated economies of scale. These plants will need ways to market their hydrogen, because such plants are likely to be built before a dedicated, national hydrogen transmission and distribution system is fully functional.

One potentially attractive means for moving central station hydrogen into the economy is to add hydrogen to the existing natural gas system, allowing it to be consumed along with natural gas in existing natural gas appliances. This is possible because mixtures of natural gas and 20-30% hydrogen are known to behave acceptably in many existing natural gas appliances. In the long term, pure hydrogen may also be run through existing natural gas pipelines or new, long-distance dedicated hydrogen pipelines may be constructed. These options, in many ways, could fill a major gap in a national transition to hydrogen. Table 4 shows the categorical importance of the issues and challenges enunciated in this paper as they relate to each hydrogen pipeline delivery option.

Table 4 Hydrogen Pipeline Delivery Options and Associated Research and Development Priorities

Issue/challenge	Hydrogen Pipeline delivery option	
	H_2 / NG Mixture	**Dedicated H_2 Pipelines**
Safety – materials reliability, odorants, diffusion losses	V	V
Operation and Maintenance – leak detection, materials, inspection , remote sensing, compression, hydrogen metering	I	I
Transmission and Distribution Technology – compression, separation*, hydrogen metering, inspection	V	V
Security	V	V

* - not applicable for dedicated hydrogen pipelines NG – natural gas
V – Very important; I – Important

While these approaches may be viable, technical unknowns abound, and related codes and standards development would be required. This paper has outlined a number of the challenges that would be faced before each approach could be seriously considered. Because these approaches are potentially attractive and, because so many issues would need to be resolved before such options could be adequately evaluated, it is recommended that a related analysis, research, and development and demonstration program be initiated in the near future.

The potential areas of research for a hydrogen pipeline delivery R&D program, similar to the existing DOE Natural Gas Delivery Reliability R&D Program, can be divided into the following categories:

- Inspection technologies
- Remote sensing
- Materials development
- Operational technologies
- Separation technologies
- Hydrogen metering technologies

Table 5 shows a relationship between potential areas of hydrogen research and each related area of the existing DOE Natural Gas Delivery Reliability R&D Program.

Table 5 Relationship between Potential Hydrogen Research Areas and Existing DOE Natural Gas R&D Program

Research Areas	Inspection Technology	Remote Sensing and Leak Detection	Materials Reliability	NG/H_2 Separation	Compressor Technology
Safety	v	v	v		
Operation and Maintenance	v	v	v		v
Transmission and Distribution Technology	v	v	v	v	v
Security	v	v	v		

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